ThI 8:30 AM - 10:30 AM

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Photonic Bandgap Devices

Ben Eggleton, *OFS, USA, Presider*

ThI1 (Invited) 8:30 AM

Photonic Bandgap Microcavity Devices

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Modern semiconductor microfabrication techniques can be used to define the high quality optical components needed in nanophotonic integrated circuits. Here we show our work on design, fabrication and characterization of ultrasmall lasers, filters, modulators and waveguides in photonic crystals.

When combined with high index contrast slabs in which light can be efficiently guided, microfabricated two-dimensional photonic bandgap mirrors provide us with the geometries needed to confine and concentrate light into extremely small volumes and to obtain very high field intensities. Fabrication of optical structures has now evolved to a precision which allows us to control light within such etched nanostructures. Sub-wavelength nano-optic cavities can be used for efficient and flexible control over both emission wavelength and frequency, and nanofabricated optical waveguides can be used for efficient coupling of light between devices. The reduction of the size of optical components leads to their integration in large numbers and the possibility to combine different functionalities on a single chip, much in the same way as electronic components have been integrated for improved functionality in microchips. The past rapid emergence of optical microcavity devices, such as Vertical Cavity Surface Emitting Lasers (VCSELs) can be largely attributed to the high precision over the layer thickness control available during semiconductor crystal growth. High reflectivity mirrors can thus be grown with sub-nanometer accuracy to define high-Q cavities in the vertical dimension. Recently, it has become possible to *microfabricate* high reflectivity mirrors by creating two- and three-dimensional periodic structures. These periodic "photonic crystals" can be designed within materials systems with high refractive index contrast. This opportunity allows photonic bandgaps materials to be defined, with frequency ranges within which the propagation of electromagnetic waves is forbidden irrespective of the propagation direction in space to be defined. When combined with high index contrast slabs in which light can be efficiently guided, manufacturable two-dimensional photonic bandgap devices provide us with the geometries needed to confine and concentrate light into extremely small volumes and to obtain very high field intensities. Here we describe the design, the fabrication and the characterization of functional optical devices, such as lasers, modulators, add/drop filters, polarizers and detectors based on photonic crystals.

We will show that the design and fabrication of optical structures has evolved to a precision which allows us to control light emission from etched nanostructures. For example, sub-wavelength nano-optic cavities can be used for efficient and flexible control over both emission wavelength and frequency. Similarly, nanofabricated optical waveguides can be used for efficient coupling of light between devices. This new capability enables the reduction of the size of optical components and leads to their integration in large numbers, much in the same way as electronic components have been integrated for improved functionality to form microchips. As high-Q optical and electronic cavity sizes approach a cubic half-wavelength the spatial and spectral densities (both electronic and optical) increase to a point where strong light-matter coupling becomes possible. We have developed new optical cavities with Q values above 20,000, and mode volumes as small as two to three cubic half wavelengths. With new designs, we have demonstrated optically pumped photonic crystal lasers with low threshold powers lasers, with threshold powers below 0.1mW. We have also incorporated self-assembled quantum dot emitters into our photonic crystal cavities, and defined quantum dot photonic crystal lasers. To verify our modeling predictions, we have also used near field scanning optical microscopy to locally probe the optical fields in our photonic crystal nanocavities. All of these efforts have been aimed at developing the discrete components which are expected to be used in future nanophotonic systems.

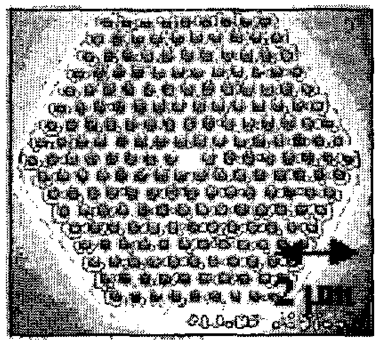

Figure 1. Photonic crystal nanocavity laser structure fabricated in InGaAsP.

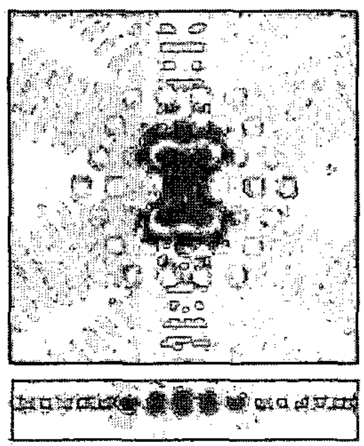

Figure 2. Modeling results showing a dipole mode in a photonic crystal cavity. 3-D finite difference time domain model.

ThI2 9:00 AM

Photonic Crystal Polarization Beam Splitters and Their Applications: First Industrialization of Photonic Crystal Devices

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We have developed novel polarization beam splitters consisting of photonic crystals and proved several attractive properties. We report their characteristics and several practical applications such as an isolator, a polarization beam combiner, and a state-of-polarization sensor

1. Introduction

Photonic crystals (PCs) are artificial multi-dimensional structures having periodicity of permittivity, whose period is of submicron order corresponding to half a wavelength in the media. The optical properties of PCs such as light localization, high dispersion, and anisotropy depend on the structural parameters such as the depth of modulation of refractive index, period of modulation, and lattice type of the modulation. In other words, we can control the properties of PCs by adjusting the parameters and thus obtain extensive freedom in designing optical devices. Although PCs have attracted much attention in the last ten years, there is still no industrialized product utilizing PCs except photonic crystal fibers, due to the difficulty of fabricating periodic nano-structures.

We have developed a unique method for fabricating PCs named autocloning [1], and recently have shown the feasibility of industrialization of PCs. In this paper, we report on practical PC polarization beam splitters and unique devices developed by using the splitters.

2. Polarization beam splitter

Fig. 1 shows a schematic diagram of our 2D PCs. Wavy films are stacked alternately, and the structure has periodicity of refractive index in the x and z directions. The operation of the polarization beam splitter arises from the anisotropy of the photonic band structure [2, 3]. When light is launched in the z direction, TE and TM modes for which the electric or magnetic vector is parallel to the y axis, respectively, have different band structures. This yields several frequency ranges where only one of the two modes is in the pass band. Therefore, if we launch light with in such a frequency range, only the polarization component in the pass band propagates through the structure, while the other component is reflected.

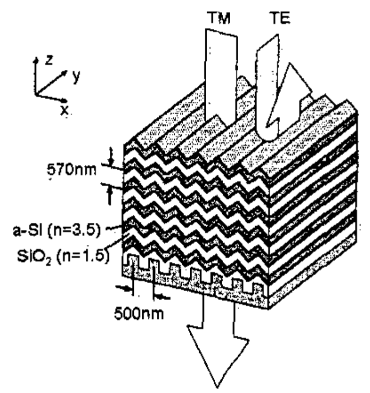

Figure 1. Schematic drawing of an autocloned 2D photonic crystal which acts as a polarization beam splitter.

Autocloning is based on a bias-sputtering process, that is, a combination of sputter deposition and sputter etching [4]. First of all, we pattern a substrate periodically, and stack a multilayer on the substrate under autocloning conditions. Under these conditions, the effect of deposition and that of etching are in some sense balanced, and the corrugated stationary shape is preserved automatically while the multilayer is progressively stacked. Accordingly we can easily and reliably obtain multidimensional structures having submicron period.

This type of polarization beam splitters has the following features.

(1) The device is planar, and so can be treated in way as a mirror.

(2) A device having a uniform large area (20 mm square, for example) can be obtained.

(3) Excellent characteristics (low insertion loss and high extinction ratio) are achieved.

(4) Various materials such as magnetic garnet crystal can be used for the substrate.

(5) The device can be designed with a high degree of freedom because the optical axis and operating wavelength can be controlled by adjusting the substrate pattern.

(6) Sputtering process is well established, which offers prospects for high productivity.

The structure of the beam splitters is as follows. The pitch of the substrate pattern is 500 nm and the stacking period 570 nm (Si: 228 nm, SiO_2: 342 nm). We stacked 12 pairs (about 7 microns thick) of a-Si and SiO_2 alternately. Fig. 2 shows a